OPERATIONAL FORECAST OF BEACH MORPHODYNAMICS. RELIABILITY AND PREDICTION LIMITS

A. Sánchez-Arcilla[1], V. Gràcia[1], M. Grifoll[1], M. García[1] and E. Pallares[1]

The paper presents a nested and coupled modelling suite including meteorological, waves, currents and morphodynamics sub-routines. The sequence has been applied to two distinctive beaches along the Catalan coast in the Spanish Mediterranean. Models and observations from two intensive campaigns have been compared to establish the accuracy and reliability of morphodynamic simulations, with the aim to determine uncertainty intervals and to assess the suitability of using such a modelling tool for reducing storm induced risks in beach management.

Keywords: Operational, morphodynamics, wave, current, reliability.

INTRODUCTION

The operational prediction of beach morphodynamics is an important asset for the proactive management of coastal zones, including risk reduction in front of incoming storms. Thanks to the advances in numerical tools and coastal observations, including data assimilation and high resolution modelling, it is nowadays becoming possible to implement operational morphodynamic predictions and to derive from that an early warming system which is relatively new in coastal environments (Ciavola et al, 2011; Vousdoukas et al, 2012).

Such modelling approach is based on a structured mesh nested sequence of models (alternatively an unstructured mesh) with coupling whenever the dominant processes require it. Each model has also its own calibration requirements and the end result can depend critically on the nesting, coupling and tuning strategy. Meteorological models show important discrepancies with observations for situations of sharp topographic gradients and impulsive types of events, typical of the Mediterranean coast. The wave generation codes tend to show under prediction for storm events and a general over prediction for calmer conditions, with larger errors for situations of winds blowing from land (fetch limited generation) so typical also of the Spanish Mediterranean coast. Circulation models tend to provide a reasonable overall pattern but the "details" of small scale features, important for velocities and mean water levels near the coast are often poorly simulated. The integration of all hydrodynamic results into a morphodynamic set of equations raise the error by at least one order of magnitude, due to the combination of uncertainties in the drivers and, mainly, to the uncertainties in sediment transport formulations. This is particularly serious for beaches with more than one sediment size and where the sediment deposit coexist with vegetation (sea grass, etc…) and rocky out crops so often found in Mediterranean coasts.

To illustrate the present reliability and prediction limits of morphodynamic operational simulations the paper will present the application of such an operational morphodynamic tool at two distinct sites along the Spanish Mediterranean coast: a barrier beach within the Ebro Delta and the Badalona beach, where the natural and manmade structures significantly affect the resulting water and sediment fluxes. The analysis is done by reproducing the observed hydrodynamic and morphodynamic response of these beaches due to the impact of different recorded storm conditions some of which reported important damages. The first case is experiencing erosion and breaching events, while for the second one the beach oscillations as a result of prevailing waves affect the sea front promenade and the buildings right behind it.

METHODS

The operational modelling sequence combine the WRF meteorological model (Dudhia, 1993), the SWAN model for wave generation and propagation (Booj et al, 1996) and the ROMS model for near shore circulation (Shchepetkin and Mc Williams, 2005). The morphodynamic model selected is XBEACH (Roelvink et al., 2009), able to simulate the more relevant processes responsible for beach profile dynamics. An overall and individual model performance for the main storms that have produced an important morphodynamic impact in the last 20 years for the barrier site has been performed. These cases will allow establishing the prediction limits for such simulations with emphasis on the obtained morphodynamic patterns. The same event approach will be used for the urban

[1] Laboratori d'Enginyeria Marítima, Univeristat Politècnica de Catalunya, C/Jordi Girona 1-3, Barcelona, 08034, Spain

(Badalona) beach, where the available sand volume and berm width are the main criteria for managing the beach.

Study area

The Catalan coast (northwestern Spanish Mediterranean Sea) has a total length of about 700 km 35% of which are sandy beaches. From those 250 km more than the half can be considered as urban or urbanized with all sort of infrastructures (seafront promenades, roads, buildings, etc).

The relatively low annual mean wave conditions, with Hs of about 0.8 m and associated Tp of about 6 s, with the small tidal range (less than 0.5 m) makes the coast to be considered as a friendly environment with no risk. However, storm events can reach values 6 times higher than mean conditions and usually are developed in only few hours. Besides, the strong winds responsible of these high energetic waves typically affect the coast inducing a meteorological tide of up to 1 m. These storm wave characteristics in conjunction with not adequately planed infrastructures (most of them were originally designed ignoring the action of waves) has made the coast highly vulnerable. Figure 1 shows the storm effects along the Catalan coast for the event of 2001, one of the major storms registered by the existing oceanographic network with maximum offshore waves heights of up to 10 m and periods of about 14 s coming from the East. The storm moved from North to South for almost a week producing damages in many coastal defense structures as well as minor facilities (urban furniture) and in some beaches producing important flood events with massive sand accumulations at the backside of the beaches. A similar coastal response has been observed for other extreme storms in 2003 and 2008 being the total reported kills of 6 persons during the last 10 years.

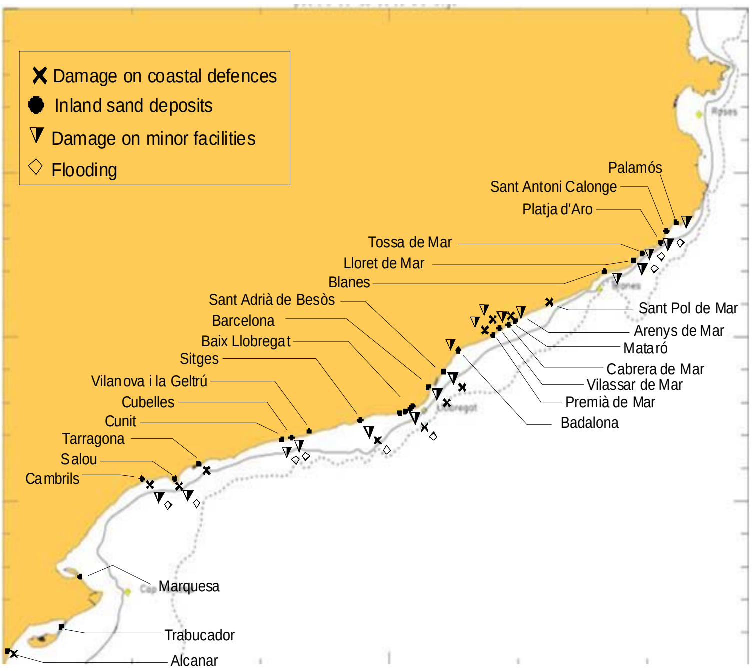

Figure 1. Study area showing the shelf domain and the main coastal villages suffering damages from wave and surge storm impacts.

The study has been focused at two distinct sites along the Spanish Mediterranean coast: The Trabucador bar and the Badalona beach. The Trabucador bar, located within the Ebro Delta (200Km South of Barcelona) is one of the best preserved barrier beaches of Spain with a length of about 5 km and a mean width of about 200 m. The barrier has a mean sediment grain size of about 210 µm and can be considered as a classic dissipative beach with up to two submerged bars at the seaside and a very shallow zone at the bayside. Apart from its natural value the barrier is used as the main road connecting the existing salt industry at the south spit with the mainland. At the emerged part the barrier has an artificial sand dune originally designed to prevent the road from wave attacks although nowadays is completely destroyed in the central part of the barrier. Due to this and after any breaching episode, the continuity of the barrier is restored by simply refilling the breaches with the over-washed sediment.

The Badalona beach, a few Km North of Barcelona, can be considered as the typical urban beach in Spain with a seafront promenade at the backshore at +5m above the mean sea level connecting the city with the coarse sandy beach (medium diameter of about 350 μm). There is an instrumented coastal pier that can provide field observation across the surf zone which allows gauging the vulnerability to storm events.

The first case is experiencing erosion and breaching events, while for the second one the beach oscillations as a result of prevailing waves affect the sea front promenade and the buildings right behind it.

Wave modelling

The model used to simulate wave generation/propagation in the coastal area has been SWAN. The SWAN code (Simulating Waves Nearshore; Booij et al., 1999 and Ris et al., 1999) is a third-generation wave model that computes random, short-crested wind generated waves in coastal regions and inland waters. It is based on the wave action balance equation and incorporates the triad wave-wave interactions plus depth-induced breaking. One of the main aspects for choosing the model for this study is that it can work in the presence of ambient current, taking into account part of the effects that these currents have on the wave field, and it is, thus, suitable for coupling with the oceanic model ROMS.

The wave simulations have been structured in five different domains covering all the North Western Mediterranean Sea. The first one is a large domain all over the mentioned area with a grid resolution of 9 kilometers. This domain is employed to generate boundary conditions for the smaller domains. The second domain is located in the Balearic Sea, with a mesh size of 3 kilometers. The next one is a domain following the Catalan Coast and shelf represented by an irregular grid with a mean cell size of 1 kilometer. The lasts ones are two small domains located near the coast, in the two selected areas of interest: the Ebro Delta and the Barcelona-Badalona coast. The grid size of the smallest domains is 250 m and 50 m respectively. In figure 2 you can observe the location of each domain.

Figure 2. Distribution of numerical modellling domains, covering the full western Mediterranean (to generate realistic offshore boundary conditions) and nested till reaching the topographic and bathymetric "details" along the Catalan coast.

Curvilinear grids have been used in the domains located over the shelf and coastal areas. The reason for using this type of grids is identical to the ones employed for the circulation code, is to reduce geometric and interpolation areas in a coast with sharp spatial gradients.

Within the FIELD-AC European research project, which is the basis of this work, two measurement campaigns have been developed in the area between November 2010 and April 2011. The instrumentation used for the campaigns were two AWACS (A1 and A2) located in front of the coast, at 20 m depth, and one directional buoy (A3) located slightly farther from the shore, at 40 m depth.

The simulations have covered the campaigns period, in order to validate the results with the data obtained from the additional instrumentation. Also buoy data from the permanent instrumental network

XIOM (Xarxa d'Instruments Oceanografics i Meteorológics, www.xiom.cat) has been used for validation and calibration activities.

Current modelling

The circulation over the Catalan coast have been analysed considering the main meteo patterns. Near-inertial motions, associated with active wind events, are the dominant fluctuations over the shelf and slope of the Catalan Sea (Salat et al., 1992; Rippeth et al., 2002). A south-westward flow due to the influence of the quasi-permanent Northern Current (Millot, 1999) has been described over the slope with lower density water being found onshore of the current (Salat et *al* 1992). The Northern Current is in geostrophic equilibrium with a shelf/slope density front, with the surface signature of the front located between 28 km and 55 km offshore (Rubio et *al* 2005). Using circulation model simulations, Jordèa and Demey (2010) found considerable meso-scale activity (eddies, filaments, and meanders) over the slope and outer shelf region. The mid- and outer Catalan shelf was conceptually analyzed by Sàanchez-Arcilla and Simpson (2002) at south of our study area in a region strongly influenced by the freshwater outflow of the Ebro River (south margin of the Catalan Sea). The inner-shelf is strongly polarized in the along-shelf direction due to the coastal boundary constrain. The along-shelf current fluctuations are basically controlled by wind stress in a short time scales and by remote pressure gradients in a synoptic time scales (Grifoll et al., 2012). The observational study presented by Grifoll et al. (2012) revealed that the standard deviation in the along-shelf direction was between 2 and 6 times larger than the cros-shelf direction.

Figure 3 shows the dispersion diagram from 3 ADCP measurements located north of Badalona Beach during one month measurements. The mooring location depth was 24 meters for two shallower deployments and 50 meters water depth for the third one. In this case vertical shear was appreciated and affected by strong vertical density gradients. In this case, the wind is not able to destroy the water stratification due to the local heating.

A model with a resolution of 250 meters has been implemented in front of Barcelona-Badalona (called COASTAL model). The model includes 207 x 152 grid cells covering the area where the ADCP were deployed and is rotated 66º from the north clockwise (see sequence of numerical domains in Figure 4). The vertical coordinate has 20 sigma levels which resolves both surface and bottom boundary layers over the continental shelf. The open boundaries of the COASTAL model domain are forced by the ocean general circulation model (OGCM) described by Tonani et al. (2008) with a horizontal resolution of 1/16º ×1/16º and 71 un-evenly spaced vertical levels with 20 levels with a 3-m resolution near the surface; the model output is saved as daily-averaged temperature, salinity, sea-level and horizontal velocity fields.

The model is a global Mediterranean Sea model assimilating sea level altimeter data and surface temperature. Instead of nesting the coastal domains of interest directly in the OGCM domain, an intermediate domain (called CATalan SHElf model, SHECAT), at the scale of Catalan Shelf (see numerical domain in Figure 4) has been implemented with a 1.25 km horizontal grid mesh and 20 vertical levels. This domain represents well the physical interactions between the general circulation (basically the Northern Current) and the shelf circulation over Catalan Shelf following a nesting ratio of 5. The regional simulation provided high-frequency (4 h) outputs in order to force the COASTAL model. After the interpolation the normal velocities are adjusted to preserve the total mass flux from the coarse grid across the open boundary (Mason et al., 2010). The COASTAL model provides information to the LOCAL refined models that solves the hydrodynamics in front of Besós river (marked in Figure 3 with a line) and the ADCP positions included in the domain.

Morphodynamic modelling

A morphodynamic operational system (MOS) has been built to determine the impacts of different storms on the selected beaches. MOS is structured as a sequence of units solving the main controlling physical processes (meteorology, hydrodynamics and the morphodynamics) and an integration module which considers the results previously obtained to derive a set of beach indicators useful for decision and policy makers (Figure 5). The selected model for solving the morphodynamic response of the beach in this application is XBEACH.

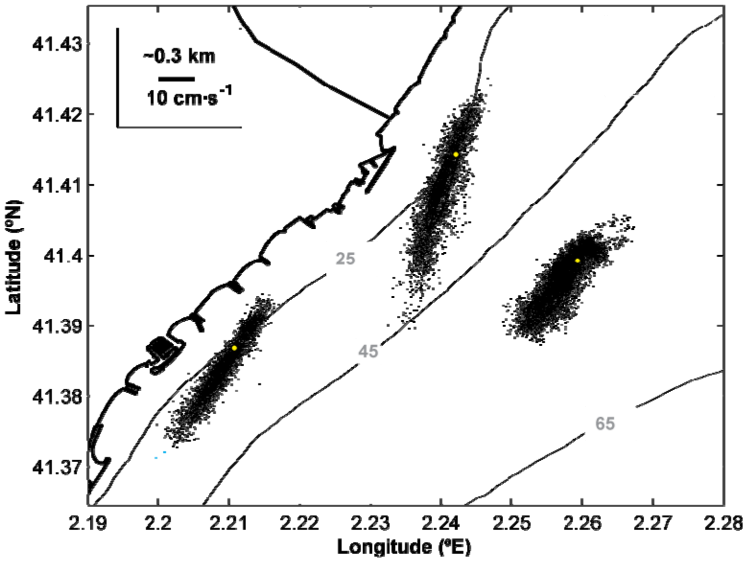

Figure 3. Dispersion diagram and variance ellipses for the depth averaged currents computed from ADCP measurements during the Field_AC campaigns. The bathymetric and boundary "steering" is apparent at all depths.

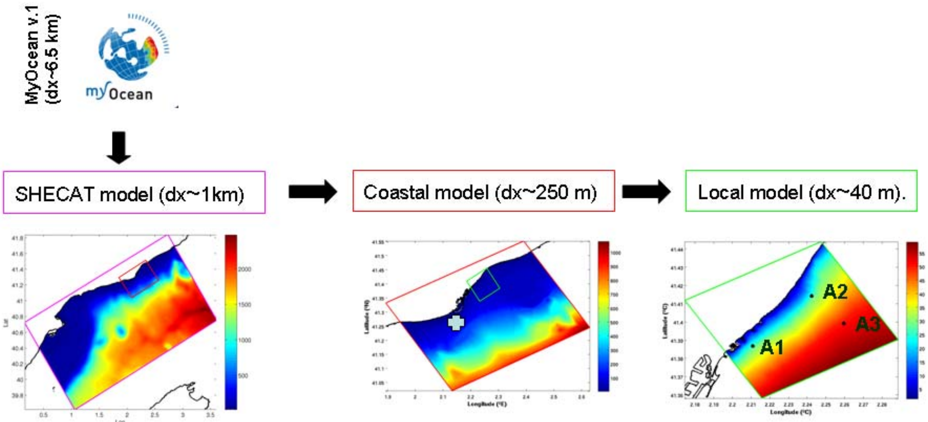

Figure 4. Nested modeling sequence developed for the Catalan coast. It is linked to the MyOcean operational system that provides the offshore boundary conditions for the currents. The bathymetry and numerical domains correspond to the domains denoted as SHECAT (shelf), COASTAL (inner shelf) and LOCAL (nearshore, including the surf zone). The ADCP sensor locations are shown in the figure (A1, A2 and A3) and also de Llobregat buoy from the XIOM network (cross symbol).

XBEACH is a two-dimensional model for wave propagation, long waves and mean flow, sediment transport and morphological changes of beaches (especially erosion, overwash and breaching) during storms. A set of formulations for the short wave envelope propagation and nonstationary shallow water equations are used in the hydrodynamic module, with a time depended wave action balance solver allowing simulating the propagation and dissipation of wave groups. Wave-current interactions are also considered. The formulation used in the transport model corresponds to the van Rijn (2007) and Soulsby (1997); this subroutine solves the 2DH advection-diffusion equation giving as a result a 2DH transport vector field throughout the domain. Avalanching conditions are also implemented for solving critical slopes.

The coordinate system used in XBEACH is curvilinear. This option allows capturing trends and morphological signs with a smaller number of nodes. Usually the distribution of nodes is less dens for the offshore region of the beach (with typical values of 50mx50m) whereas for the shallow region the grid density typically reaches 5mx5m. For the emerged part, a high resolution digital model terrain provided by the ICC (Institut Cartographic de Catalunya) is used allowing typical cells of 2mx2m. Table 1 presents the grid dimensions used in each of the beach sub zones.

	Domain length (m)	domain width (m)	Max. depth (m)	Max level (m)	nx (Longshore)	ny (Cross-shore)	mean values Cross (m)	mean values Long (m)	nº nodes
Badalona	2947	1443	-29	7,614	132	104	10,93	28,34	13728
Trabucador	4460	6070	-15	2,25	252	316	7,20	19,80	79632

Table 1. Mean Grid characteristics per beach zone as used in XBEACH.

From the model setup of Table 1 it can be seen that the processes affecting the studied beaches can be described in a very detailed manner. Because of that, the estimation of risk has to be normally carried out in a more aggregated manner, that in our case has been a set of beach indicators which can be grouped in two categories: hydrodynamics (wave, currents and mean sea level characteristics) and morphodynamics (shoreline location, sediment volume variations).

Unfortunately there is no information on the topography and bathymetry of the beaches right befor and after the impact of the storms. However, an extensive set of qualitative information from many sources is available (mainly photographs and movies). They allow to characterize (up to a point quantitatively) storm damages during the impulsive events here studied and from this tune and validate the modelling sequence.

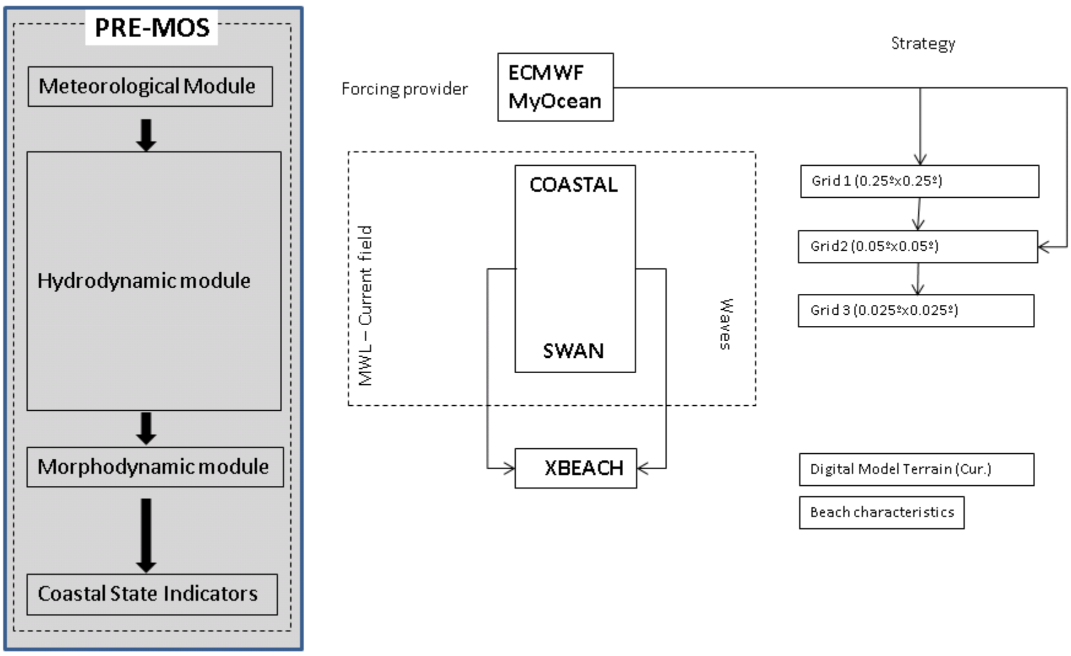

Figure 5. Flow diagram of the morphodynamic modeling suite MOS. The right hand part of the figure shows the grid sizes for the nesting and how the beach geometry is introduced into the code. The iterative arrows are not shown for clarity.

RESULTS

The different models included in MOS have been analyzed independently for different wave conditions in order to rank errors and to identify the most relevant processes within each. Results are shown in terms of waves, wave-current interactions and morphodynamics. The morphodynamic module provides an integration of results that can serve to assess the role of the different uncertainties in the final prediction.

Waves

The results obtained from the preliminary wave simulations at the platform domain, with a grid resolution of 1 km, show that near the coast the errors are higher than the ones observed in open waters. A comparison has been done between the results obtained in two different locations where two buoys from the local instrumental network (XIOM) are deployed. After comparing the results from a buoy located in front of the Llobregat Delta (45 m depth) and another buoy a little bit farther away from the Tarragona coast (700 m depth), the NRMSE (root-mean square error normalized by the 95% *Hs* quartile is around 11% near the coast while it is only 8,8% in the buoy located 48 km away the coast. A similar behavior is observed in the peak period where the NRMSE varies from 32% in the coastal buoy to 24% in the offshore one.

From the results of the coastal domains without considering ambient currents shown in figure 6, where the simulations have been compared with the data obtained from the AWAC (A1), one can conclude that the significant wave height is almost always under predicted; however, the under prediction is higher during storm events, reaching error values up to 100% in significant wave height.

A non-dimensional error has been calculated as the difference between the simulated and the measured data and normalized by the measured value for the significant wave height and the peak period at different locations. In figure 7 the results for a characteristic month are shown. Whereas the errors in significant wave height are mostly present during storm events, the error in the peak period is almost always constant. There are no important errors in wave direction, considering the uncertainties already present in the observations.

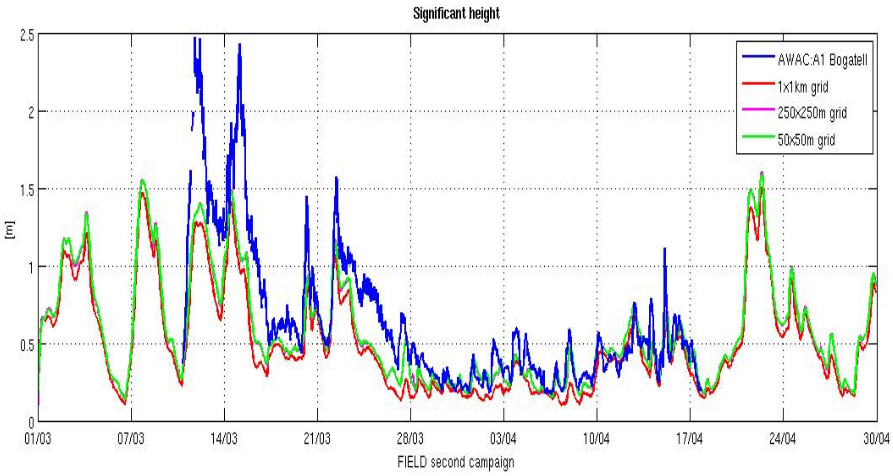

Figure 6. Significant wave height obtained from the different coastal and near shore domains compared with the AWAC measurements at about 20m depth (in blue and represented by the upper line). The under prediction gets larger for rapid development storms and for twin storm events.

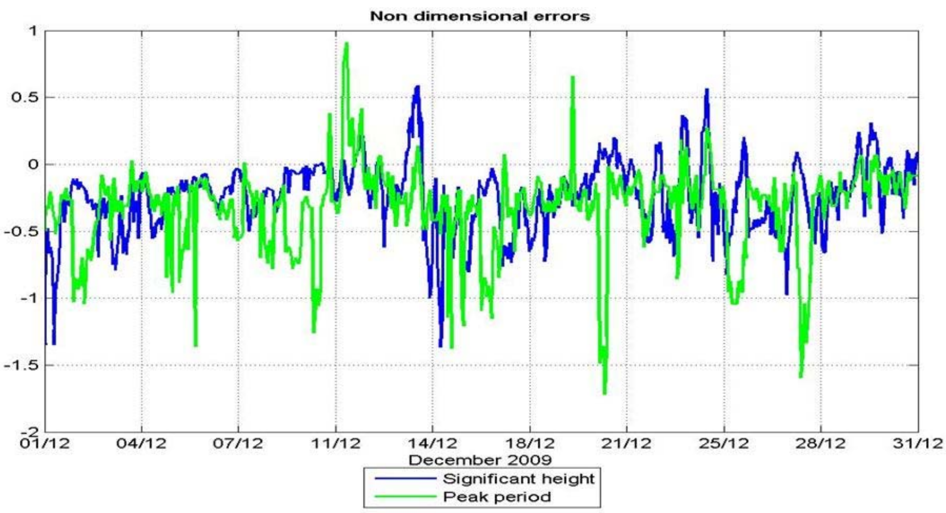

Figure 7. Plot showing the non-dimensional error for significant wave height and peak period. It corresponds to the costal domain and it has been obtained by comparing measurements and simulations at the AWAC A1 deployment point, with a depth of about 20 meters.

Currents

Time series of modeled and observed flow velocities are compared in order to estimate the error level of the simulations is presented in figure 8. Alongshore velocities at the Llobregat (50m depth) buoy and model observations are shown in Figure 7 (from 10th October 2010 to 11th April 2011), at 1 and 15 m depths respectively. A qualitative agreement between data and observations are clearly appreciated.

In general terms the longshore current shows a saw tooth time evolution, with peaks that are reasonably well reproduced by the model. This happens for the two depths at which there are observations and gives a robust result for "pure" wave induced conditions. However the agreement degrades for situations where the wind induced current, due to the intense wind velocities and the shallow depths, becomes also important. Particularly for the complex wind patterns so typical of Mediterranean conditions, where there is an over prediction at small depths and an improvement in the fit between modeled and measured velocities for greater depths.

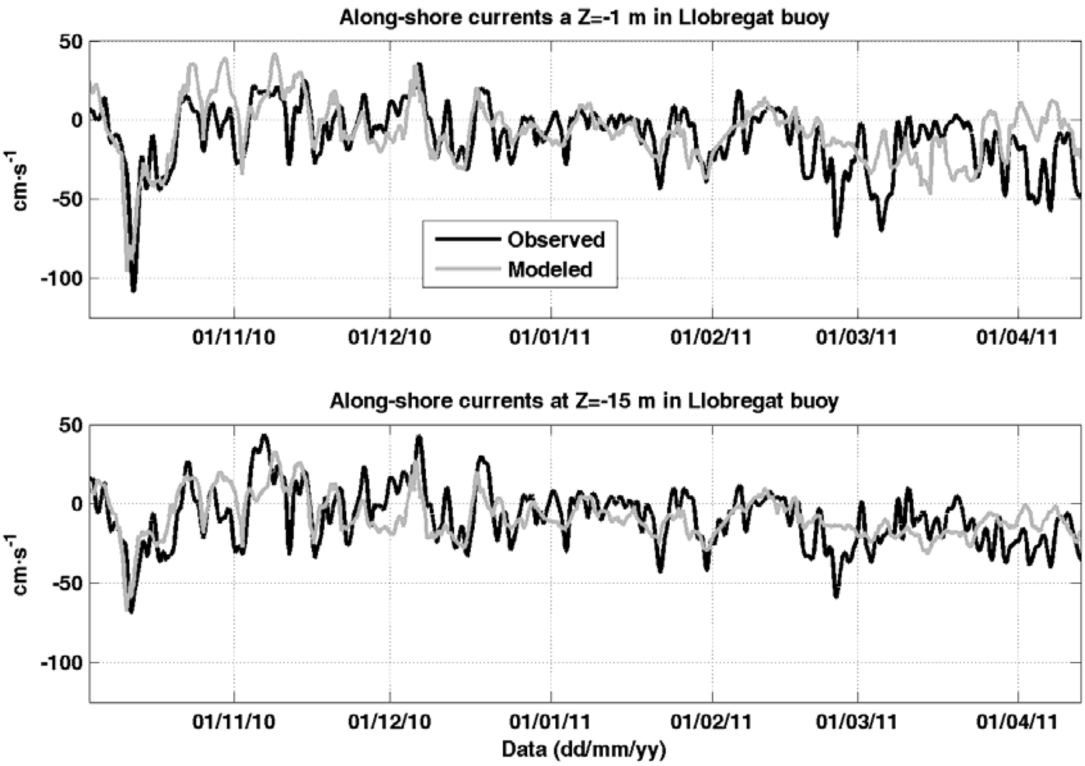

Figure 8. Time-series of observed and modelled flow in the Llobregat buoy deployed at about 50m depth and for two different levels below the face surface (1m and 15m respectively).

Morphpdynamics

Figure 9 shows the predicted bottom morphology off the Trabucador bar (in the Ebro delta coast) for the storm of 2003. As it can be seen from the figure the model is able to reproduce the main morphological features (shape, density, dimensions) like small breaching channels and washover sediment deposits in the bay side. Another important aspect to consider is the distribution of breaching along the barrier. Due to its bathymetry the barrier typically breaches more intensively in its central part which is also observed in the modeled evolution. We have also assessed the quality of the performance of the model for different storm conditions obtaining a global brier skill score index of 0.44 which according to van Rijn et al. (2003) can be considered as a reasonable prediction.

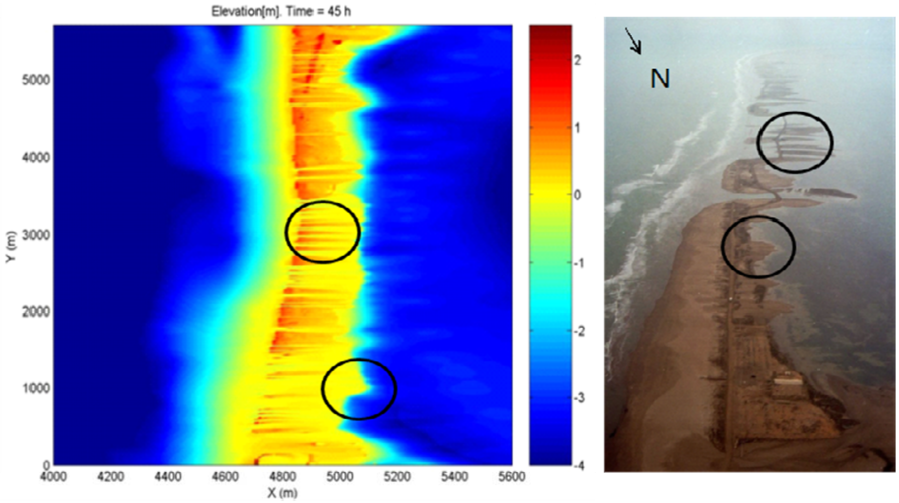

Figure 9. Predicted morphology (right) of the Trabucador bar due to the impact of the 2003 storm and observed barrier configuration after the actual breaching produced by that storm.

Figure 10 shows the results obtained at the Badalona Beach for the storm of 2008. MOS has been able to reproduce an important beach scarp at the upper part of the beach, indicating a high water level in coincidence with high incident waves. Unfortunately no information of the post storm beach profile recovery was available. However, the existing photographs for the same event at the same beach indicate that an intensive wave run up took place although no overwash was recorded along the beach. This coincides with the model simulated results.

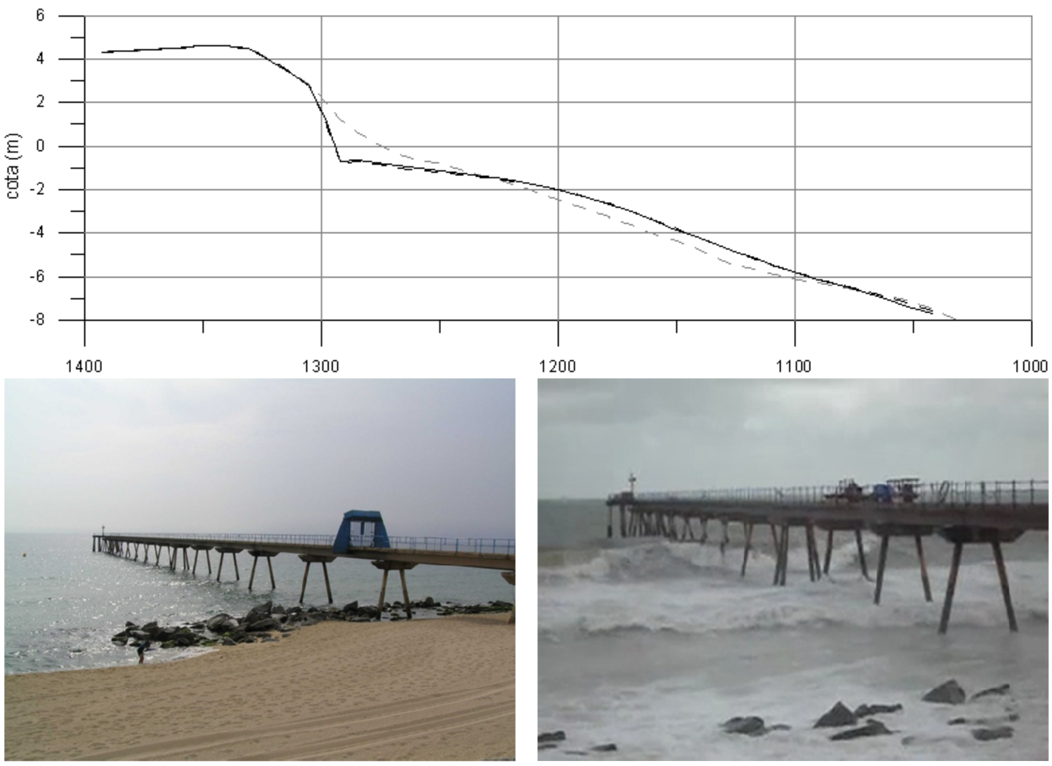

Figure 10. Modeled beach profile at Badalona beach (prior is the dashed line and the profile during the storm is the solid line) and recorded photographs from the digital video in the instrumented pier before and during the December 2008 storm.

The calculated temporal evolution of wave run up for the all Badalona beach domain is shown in figure 11. The peak of the time series corresponds, as expected with the highest wave heights. The along beach time averaged value (in red) reflects the variability within the beach, that shows areas with much higher water excursions, corresponding with the areas reporting higher damages. From a risk management perspective this indicates the caution required when presenting aggregated values or indices. The uncertainty is also apparent from the 95 and 99 confidence bands shown in the figure, which reflect the underlying probabilistic uncertainty. This again calls for caution when proposing beach or risk management decisions based on inevitably uncertain information.

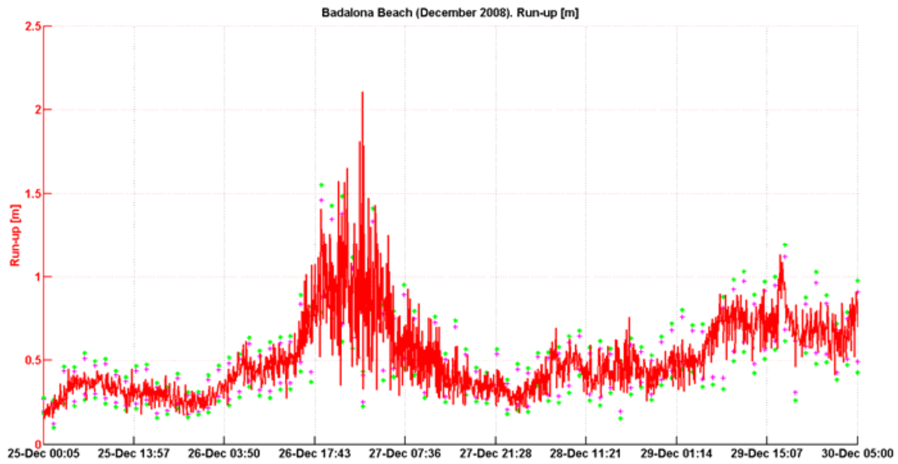

Figure 11. Temporal evolution of wave runup at Badalona beach during the storm of December 2008. Solid line: mean value; magenta: 95% confidence band and green 99% confidence band.

CONCLUSIONS

The performed simulations show how improving the resolution and the nesting sequence leads to more accurate and robust results. However when improving the mesh resolution without due consideration to the “internal” boundary conditions there may be no clear improvement in results and sometimes even a degradation of the final predictions.

The errors in the wave fields can be summarized by under prediction during the peaks and over predictions during the mightier conditions. The error in peak period appears to be steadier while the errors in direction are limited to one directional sector of 22,5 degrees, comparable to the accuracy of many of the observations. Because of that it is easier to compensate the errors in wave height predictions (and therefore also in the associated wave induced circulation in the near shore) than those due to multiple drivers such as for instance the circulation field due to wind and waves. In spite of that the MOS has reproduced qualitatively the beach response implant and profile for a variety of sediment sizes (D_{50}) and for selected storms in the period 1990-2008.

From a management perspective the averaging and time and space of the hydrodynamic and morphodynamic results will lead to a process-based indicator that provides advanced information on the drivers and beach response for processes such as erosion and flooding. These indicators therefore, can be used by beach authorities and municipalities to prepare the beach for the incoming storm, within the time horizon of normal meteo-oceanographic predictions, which goes from 3 to 5 days. The required averaging to produce the indicators should be carried out with caution, since for beaches with important along shore variations or transient behavior during the storms the averaging may “falsify” the true morphodynamic behavior and therefore it is necessary to associate confidence bands to the proposed index values. That should also provide a more robust indicator to indicate the beach manager the range of variability upon which a management decision is based.

ACKNOWLEDGMENTS

The authors want to acknowledge the support of many institutions in Madrid and Barcelona that have contributed insight and data. This includes the Catalan Meto Service (SMC), the Geologic and Cartographic Institutes (IGC, ICC), Puertos del Estado and others. The research has been supported by the European Union project of FP 7 Field_AC (*Fluxes, Interactions and Environment at the Land-Ocean Boundary. Downscaling, Assimilation and Coupling, Contract nº 242284*) and the Spanish project COVARIANCE (*Corrientes, oleaje y viento; mejora del análisis de riesgos mediante asimilación en esquemas numéricos de la costa y su entorno, Contract nº CTM2010-19709).* The support of the students from the Master in Coastal/Estuarine Engineering and Management is also recognized.

REFERENCES

Booij, N., Ris, R.C., and Holthuijsen, L. 1999. A third-generation wave model for coastal regions, part 1: Model description and validation. *Journal of Gephysical Research*, 104, 7649-7666.

Dudhia, J., 1993: “A nonhydrostatic version of the Penn State-NCAR Mesoscale Model: Validation tests and simulation of an Atlantic cyclone and cold front”. *Mon. Wea. Rev*. 121: 1493-1513.

Ciavola, P., Ferreira O., Haerens P., Van Koningsveld M., Armaroli C. and Lequeux Q., 2011a. Storm impacts along European coastlines. Part 1: The joint effort of the MICORE and ConHaz Projects. *Environmental Science and Policy*, Volume 14, Issue 7, November 2011,912–923

Ciavola P, Ferreira O, Haerens P, Van Koningsveld M and Armaroli C. 2011b. Storm impacts along European coastlines. Part 2: lessons learned from the MICORE project. *Environmental Science and Policy*, Volume 14, Issue 7: 924-933. doi:10.1016/j.envsci.2011.05.009.

Grifoll M., A.L. Aretxabaleta, M. Espino, and J.C. Warner. 2012. Along-shelf current variability on the catalan innershelf (nw mediterranean). *Journal of Geophysical Research, 117. In press.*

Jordà, G., and P. De Mey. 2010, *Characterization of error dynamics in a 3D coastal model of the Catalan sea using stochastic modelling, Continental Shelf Research*, 30(5), 419-441.

Millot, C. *1999, Circulation in the Western Mediterranean Sea, Journal of Marine Systems*, 20(1–4), 423-442.

Mason, E., J. Molemaker, A. F. Shchepetkin, F. Colas, J. C. McWilliams, and P. Sangrà (2010), Procedures for offline grid nesting in regional ocean models. *Ocean Modelling* 35 (1-2), 1-15.

Rippeth, T. P., J. H. Simpson, R. J. Player, and M. Garcia. 2002, *Current oscillations in the diurnal–inertial band on the Catalonian shelf in spring, Continental Shelf Research*, 22(2), 247-265.

Ris, R.C., Holthuijsen, L.H., and Booij, N. 1999. A third-generation wave model for coastal regions, part 2: Verification. *Journal of Geophysical Research*, 104, 7667-7681.

Roelvink D., Reniers A., van Dongeren A., van Thiel de Vries J., McCall R. & Lescinski J. 2009. Modeling storm impacts on beaches, dunes and barrier islands, *Coastal Engineering*, 56, Issues 11-12.

Rubio, A., P. A. Arnau, M. Espino, M. del M. Flexas, G. Jordà, J. Salat, J. Puigdefàbregas, and A. S.-Arcilla. 2005, *A field study of the behaviour of an anticyclonic eddy on the Catalan continental shelf (NW Mediterranean), Progress In Oceanography*, 66(2–4), 142-156.

Salat, J., J. Tintore, J. Font, D.-P. Wang, and M. Vieira.*1992, Near-Inertial Motion on the Shelf-Slope Front off Northeast Spain, Journal of Geophysical Research*, 97(C5), 7277-7281.

Sánchez-Arcilla, A., and J. H. Simpson. *2002, The narrow shelf concept: couplings and fluxes, Continental Shelf Research*, 22(2), 153-172.

Shchepetkin, A. F. and J. C. McWilliams, 2008: Computational kernel algorithms for fine-scale, multi-process, long-term oceanic simulations. In: *Handbook of Numerical Analysis, Vol. XIV: Computational Methods for the Ocean and the Atmosphere*, P. G. Ciarlet, editor, R. Temam & J. Tribbia, guest eds., *Elsevier Science*, pp. 121-183.

Soulsby, R. L. 1997. *Dynamics of Marine Sands*. London: Thomas Telford.

Tonani, M., N. Pinardi, C. Fratianni, J. Pistoia, S. Dobricic, S. Pensieri, M. de Alfonso, and K. Nittis *2009, Mediterranean Forecasting System: forecast and analysis assessment through skill scores, Ocean Science*, 5(4), 649-660.

van Rijn, L. C., D. J. R. Walstra, B. Grasmeijer, J. Sutherland, S. Pan, & J. P. Sierra. 2003. The predictability of cross-shore bed evolution of sandy beaches at the time scale of storms and seasons using process-based Profile models. *Coastal Engineering* 47(3): 295–327.

van Rijn, L. 2007. Unified view of sediment transport by cur-rent and waves, part I, II, III and IV. *Journal of Hydraulic Engineering* 1336: 649–689 (part I & part II); 7: 761–793 (part III & part IV).

Vousdoukas, M.I., Ferreira, Ó., Almeida, L.P., Pacheco, A. 2012. Towards reliable storm-hazard forecasts: XBeach calibration and its potential application in an operational early-warning system. *Ocean Dynamics*, 61: 1001-1015.